Distributed Slack Bus Algorithm for Economic Load Dispatch

A thesis submitted in partial fulfilment of the requirements for the degree of Bachelor of Technology in Electrical Engineering

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2012

For

Maa, Bapa and Baba.

NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

CERTIFICATE

This is to certify that this thesis entitled "**DISTRIBUTED SLACK BUS ALGORITHM FOR ECONOMIC LOAD DISPATCH**" submitted by ANURAG MOHAPATRA, 108EE005, for the partial fulfilment of the requirements for **B.Tech in Electrical Engineering** during session 2011-2012 at National Institute of Technology, Rourkela (Deemed University) is an authentic work by him under my supervision and guidance.

Signature of student **Signature of the supervisor**

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ABSTRACT

The power flow in a highly interconnected grid is an ancient problem for an electrical engineer. With the advent of time of course, this issue has been tackled with greater accuracy and efficiency. Now the load flow and subsequent concerns are taken care by simulations in a minute. The next big obstacle is that of Economic Load Dispatch. In ELD, the unit commitment of each generator is taken into consideration to have adequate margin for reserve at any time. The second issue with ELD is with allocating the total generation to the individual generators in such a way that the total cost of generation at any time is at a minimum. In this project, the optimum cost of generation problem has been looked into with a distributed slack bus algorithm. In ordinary line flow analysis, the slack bus is asked to carry the entire residual burden of the system. In the proposed method, the burden on slack bus shall be eliminated and still maintain the equal incremental cost criteria. A new concept called Participation factor shall be used to achieve the same as the total loss of the system at the end of iteration shall get divided among all the generator buses. Two distinct bus networks were used as case studies and the results are compared and analysed to verify the usefulness of the proposed technique.

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PROBLEM STATEMENT

To analyse the effect of distributing the burden on the slack bus in an Economic Load Dispatch algorithm including transmission losses and compare the same with the results of existing ELD schemes using a 5 bus and 26 bus AC network system as case studies.

Chapter 1

INTRODUCTION

1. INTRODUCTION

1.1 LOAD FLOW STUDIES.

Load flow solutions in a network under steady state gives the nodal voltage and phase angles and hence power injection at every node of a grid. It is determined using equations of power balance along with certain inequality constraints like, reactive power generation, tap setting of transformers etc. This load flow solution is essential for a new system or for extending an existing system under both normal and abnormal conditions. Load flow equations are generally non-linear and hence require an iterative procedure to solve them. There are many different load flow analysis techniques, but three primary algorithms are well accepted.

1. Gauss-Seidel method.
2. Newton-Raphson method.
3. Fast Decoupled method.

Out of these, the NR method has been used in this project for solving the load flows.

1.1.1 ADVANTAGES OF USING NR METHOD.

1. The number of iterations involved is less in a NR method; thus the load flow solution is achieved quicker.
2. The number of iterations is also not much dependent on the size of the system involved.
3. As compared to GS method, NR method has a faster convergence (4^{th} order).

1.2 BUS CLASSIFICATION.

With each bus in a power system provided with a real power, active power, voltage magnitude and phase angle value, the buses can be classified into three distinct categories according to quantities specified at each node.

Bus type	Quantities specified	Quantities to be obtained
Load bus	P, Q	V, δ
Generator bus	P, V	Q, δ
Slack bus	V, δ	P, Q

Table 1.1. Classification of Buses in Power System.

1.2.1 SLACK BUS.

A slack bus is also a generator bus. It is mostly the bus with the highest generating capacity. The slack bus is considered a reference for the other buses in load flow analysis. The need of a slack bus is two-fold.

1. Since the grid is interconnected and the phase angle plays a crucial role in load flow, one bus must remain at a virtual reference zero phase angle, so that the other buses can be related with respect to this bus.
2. The losses in the system aren't calculated till the end of the iteration. The deficit in the power injection and power demand is the loss of the system. This extra power must be accommodated in the load flow for the next iteration. Hence the slack bus accepts this extra burden on itself and balances the system. So at this bus the voltage magnitude and phase angle is specified and the real and reactive power is calculated.

A slack bus is also required from the nodal admittance matrix point of view. Without a slack bus, the matrix will be singular and can't be handled. By introducing a slack bus, one row and column is eliminated and thus the system turns non-singular.

1.3 ECONOMIC LOAD DISPATCH

Economic Load Dispatch (ELD) uses two notions as its basis. Firstly, the generating units must provide for the power required in the minimum cost bracket by optimally using the units. Secondly, the units must be ready to provide a backup, albeit within a margin, if other units fall out of generation.

The first aspect is largely necessary to mitigate since with the increase in size of the grid and interconnectivity the losses also increase. Hence meeting the power needs cant be done arbitrarily just based on availability. It may so happen that the power generation cost at Station A is less than that of Station B. Naturally, the power demand must be met by Station A because it is cheaper. But if Station A is very far away from the demand point as compared to Station B, it might not be advisable to do the same because of the included transmission losses. There are many such constraints to look into before deciding on which generator will generate how much.

All in all, the ELD scheme searches for one load flow setup out of many which optimally satisfies all the technical and most of the economic constraints imposed on the system. Since total cost of generation is a function of individual generation of the sources, the system constraints will more or less decide on the total cost of the system.

1.4 SYSTEM CONSTRAINTS IN ELD [1]

There are two types of constraints:

(i) Equality constraints

(ii) Inequality Constraints:

(i) **Equality constraints:**

The equality constraints are the basic load flow equations given by

$$P_p = \sum_{q=1}^{n} \{e_p (e_q G_{pq} + f_q B_{pq}) + f_p (f_q G_{pq} - e_q B_{pq})\}$$

$$Q_p = \sum_{q=1}^{n} \{f_p (e_q G_{pq} + f_q B_{pq}) - e_p (f_p G_{pq} - e_q B_{pq})\}$$

$$p = 1,2,3,........, n$$

Where e_p and f_p are the real and imaginary components of voltage at the p^{th} node and G_{pq} and B_{pq} are the nodal conductance and susceptance between the p^{th} and the q^{th} nodes.

(ii) **Inequality constraints:**

a) *Generator Constraints:*

The kVA loading on a generator is given by $\sqrt{P_p^2 + Q_p^2}$ and this should not exceed a pre specified value C_p because of the temperature rise conditions that is $P_p^2 + Q_p^2 \le C_p^2$. If the power output of a generator for optimum operation of the system is less than a pre specified value P_{min}, the unit is not put in the bus bar because it is not possible to generate that low value of power from that unit. Hence the generator powers P_p cannot be outside the range stated by the inequality $P_{p\min} \le P_p \le P_{p\max}$ .Similarly the maximum and minimum reactive power generation of a source are limited. Hence the generator reactive power Q_p cannot be outside the range stated by the inequality i.e. $Q_{p\min} \le Q_p \le Q_{p\max}$.

b) *Voltage Constraints:*

It is essential that the voltage magnitudes and phase angles at various nodes should vary within certain limits. The voltage magnitude should vary within certain limits because otherwise most of the equipment connected to the system will not operate satisfactorily or additional use of voltage regulating device will make the system uneconomical. Thus

$$|V_{p\min}| \le |V_p| \le |V_{p\max}|$$

$$\delta_{p\min} \le \delta \le \delta_{p\max}$$

Where V_p and δ_p stand for the voltage magnitude and phase angle at the p^{th} node. The normal operating angle of transmission line lies between 30^0 and 45^0 for transient stability reasons. Therefore a higher limit is imposed on angle δ. A lower limit of δ assures proper utilization of transmission facility.

c) *Running Spare Capacity Constraints:*

These constraints are required to meet:

(i) the forced outages of one or more alternators on the system and

(ii) the unexpected load on the system

The load generation should be such that in addition to load demand and losses a minimum spare capacity should be available i.e.

$$G \ge P_D + P_{SO}$$

Where G is the total the generation and P_{SO} is some pre specified power. A well planned system is one in which this spare capacity P_{SO} is minimum.

d) *Transformer Tap Settings:*

If an auto transformer is used the minimum tap settings could be 0 and the maximum 1 i.e.

$$0 \le t \le 1$$

Similarly for a two winding transformer if tapings are provided on the secondary side $0 \le t \le n$, where n is the ratio of transformation. Phase shift limits of the phase shifting transformer.

$$\theta_{p\min} \le \theta_p \le \theta_{p\max}$$

e) *Transmission Line Constraints:*

The flow of active and reactive power through the transmission line circuit is limited by the thermal capability of the circuit and is expressed as

$C_p \le C_{p\max}$, where C_{pmax} is the maximum loading capacity of the p^{th} length.

f) *Network Security Constraints:*

If initially a system is operating satisfactorily and there is an outage, may be scheduled or forced one, it is natural that some of the constraints of the system will be violated. The complexity of these constraints is increased when a large system is under study. In this case a study is to be made with outage of one branch at a time and then more than one branches at a time. The nature of the constraints is same as voltage and transmission line constraints

1.5 METHODS OF SOLVING THE ELD PROBLEM.

The solving of the ELD problem basically rests on the equal incremental cost for each generator. The cost curves are analysed to arrive at the equal cost scenario. If the distances involved in the grid are small, then the transmission losses can be let go of entirely. Thus the ELD scheme becomes that of,

$$\text{Min } F_T = \sum_{n=1}^{n} F_n$$

$$\text{Subject to } P_D = \sum_{n=1}^{n} P_n$$

Where, F_T is total fuel input to the system, F_n is the fuel input to the *n*th, P_D is the total unit demand and P_n the generation of nth unit. By using a Lagrangian multiplier technique, we arrive at a solution where,

$$\frac{dF_1}{dP_1} = \frac{dF_2}{dP_2} = \frac{dF_3}{dP_3} = ... = \lambda$$

Here $\frac{dF_1}{dP_1}$ is the incremental cost of generation at plant 1 in unit currency/hr and so on.

But in real scenario, we cannot avoid the transmission losses and hence they do play a part in ELD analysis [2]. With the losses in the picture, the new scheme becomes that of,

$$\text{Min } F_T = \sum_{n=1}^{n} F_n$$

$$\text{Subject to } P_D + P_L = \sum_{n=1}^{n} P_n$$

Where P_L is the total system loss which is assumed to be a function of generation and the other terms have their usual significance. Solving this using the Lagrangian multiplier again, we arrive at,

$$P_n = \frac{1 - \frac{f_n}{\lambda} - \sum_{m \neq n} 2B_{mn}P_m}{\frac{F_{nn}}{\lambda} + 2B_{nn}}$$

With a certain coordination equation written as,

$$F_{nn}P_n + f_n + \lambda \sum 2B_{mn}P_m = \lambda$$

The simultaneous equations derived are then solved using standard matrix inversion routine or by using any iterative procedure. Another technique of solving the ELD problem is named as the modified coordination equation method which uses the technique of changing the bus power of one plant by small amounts keeping the other end of bus voltage constant [1]. This incremental change brings about some stable changes in the grid in long run. In this method, P_i is positive for generator and negative for load bus,

$$\therefore dP_L = \sum_{i=1}^{n} \frac{\partial P_L}{\partial P_i} dp_i$$

In an interconnected system, if we vary the power P_j with respect to P_i in small amounts, we get,

$$dP_{Lj,n} = \frac{\partial P_L}{\partial P_j} dP_j + \frac{\partial P_L}{\partial P_i} dP_n$$

Here, $dP_{Lj,n}/dP_j$ is the ratio of change in loss to the change in generation at plant j when power is transferred from plant j to plant I, with other generators at fixed loading.

Chapter 2

DISTRIBUTED SLACK BUS ALGORITHM

Burden on Slack Bus

Participation Factor

2. THE DISTRIBUTED SLACK BUS ALGORITHM

The existing ELD schemes have primarily two basic logic flaws. Firstly, only one slack bus is an unrealistic assumption. It cannot happen in a physical system that in spite of the presence of hundreds of buses, only one is assigned to carry all the losses incurred by the system. Secondly, the equal incremental cost idea is violated if we burden the slack bus with extra unaccounted load at the end of iteration.

These ideas are more and more pointing towards a new ELD scheme where the additive burden on the singular slack bus be divided among other buses also in the network. Several methods have been studied in reducing the burden on slack bus. A participation factor based on cost function coefficient of the system generators is used to the same effect in [3]. In [4], the N-R formulation is presented using a loss term. Approximation procedures can also be used as in [5]. These approximations are sometimes very lengthy to calculate though.

2.1 BURDEN ON SLACK BUS

The slack bus serves two functions in a load flow or for that matter an ELD scheme. It serves as a virtual reference for the other buses in the system with its phase being arbitrarily assigned as zero. The second purpose is of servicing as a dump for the unaccounted active and reactive power, which are the system losses. In a scheme where the incremental fuel cost has to be kept equal on all buses, by asking one bus to carry all the losses, this idea is certainly violated. Thus the perceived optimum solution is not optimum at all for the slack bus. In the prevalent ELD schemes, nothing can be done about it, because the inclusion of slack bus in the jacobian matrix will cause it to become singular and the solution will fail.

2.2 PARTICIPATION FACTOR

A participation factor is a simple algebraic ratio. It is a weight attached to each generator bus such that, the total unaccounted power shall be distributed to that bus multiplied by its respective participation factor.

In a means to deal with the distributed slack bus problem, we can distribute the real power deficit among all generating buses. While doing so we take care that the individual generating limits of the generators aren't exceeded. Once this is done, the burden on the slack bus is tremendously reduced and now it can enter the optimal cost criteria region. To do this many factors come into picture. The capacity of the individual generators, the distance from the point of demand, the interconnection index, the dependency of other grids on the said system and so on. Each of them individually or bunched together can be used to decide on a parameter which shall dictate how to divide the power loss among the buses.

From the discussion above it is quite clear that the change in this parameter will cause change in the system ELD scheme altogether. This parameter is called the participation factor which when multiplied with the loss of the system decides how much loss be transferred to the respective bus. Every different system can have a different participation factor. But the sum of all participation factors in a system must be unity. Only generator buses have a participation factor parameter.

2.2.1 DIFFERENT PARTICIPATION FACTORS.

1. Based on the distance involved in the system.

In a system all the generators aren't present at an equal distance from the demand point. To counter this, a parameter called the Penalty factor is defined as,

$$L_n = \frac{1}{1 - \frac{\partial P_L}{\partial P_n}} .$$

This parameter stands as a judge of the distance involved and hence the extra losses. While distributing the power to all the buses, the closer generators will have less cost than the farther ones. Thus a participation factor can be modelled after the penalty factor. In [6], it is defined as,

$$K_i = \frac{L_i P_{Gi}^{Load}}{\sum_{j=1}^{m} L_i P_{Gi}^{load}}$$

Where, K_i is the participation factor, L_i is the penalty factor of the bus, m is the number of generator buses present in the system.

2. <u>Based on the cost function</u>.

The cost function is approximated as a quadratic relation with active power in most cases.

$$C_n = \alpha P_n^2 + \beta P_n + \gamma$$

Since this relation holds key to the cost of producing a unit amount of power, the cost function can be modelled into a participation factor. The general idea being that a generator with less cost/hr be allotted more power than others. In [3], this is achieved by using,

$$K_i = \frac{1}{2\alpha_i \sum_{i=1}^{m} \frac{1}{2\alpha_i}}$$

3. Based on the generation capacity of the buses.

The generation capacity of a bus or the size of the generator is an oblique guide to the losses incurred by the generator. The bigger a machine, the more efficient it becomes for a constant loss. Thus with the increase in the size of a generator the cost of production decreases. When the load is distributed among the generators, the individual units are driven more towards their maximum generation limits. With a larger generator we get a bigger margin for that limit. Since the generation is not cost-efficient near the maximum limit region, it is again advantageous to give preference to a bigger generator. One such participation factor is defined in [6] as,

$$K_i = \frac{P_{Gi}^{loss}}{P_{loss}}$$

An approach similar to this is used in this project to determine the participation factor.

Chapter 3

IMPLEMENTING THE PARTICIPATION FACTOR

Change in Expressions

New Newton-Raphson Matrix

Algorithm for New N-R Matrix

3. IMPLEMENTING THE PARTICIPATION FACTOR

The participation factor in this project is based on the instantaneous active power generation of the generators in the system. At the end of each iteration, the line flow generates the individual active power of the generators in the system. This value is generated keeping in mind the ELD scheme. Now the generator is most economical for this value of active power and not its said capacity at the beginning. Thus one can say that the economical aspect of generation is maintained around this value at that instant. As the deficit loss has to be distributed across the generators, this active power value can be considered as a model for the participation factor.

$$K_i = \frac{P_{Gi}}{\sum_{i=1}^{m} P_{Gi}}$$

3.1 CHANGE IN EXPRESSIONS

With this new K_i value, the expressions and equations also change. Now the active power at each generator is,

$$P_{Gi} = P_{Gi\_scheduled} + K_i P_{loss}$$

The reactive power at the buses remains the same. The total ELD scheme can be described as in [3],

$$\text{Min } \sum_{i=1}^{m} C_i P_{Gi}$$

Subject to $\sum_{i=1}^{m} P_{Gi} - P_{load} - \Delta P_B = 0$, where ΔP_B is a power term due to K_i

3.2 NEW NEWTON-RAPHSON MATRIX

The NR matrix that was formed in conventional power flow algorithm did not take into account the slack bus as a generator bus. Hence the standard NR matrix equation was,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix}$$

Where, Jn represents a jacobian sub-matrix for the system, ΔP and ΔQ are the change in active and reactive power respectively for the system and Δδ and Δ|V| are the change in phase angle and voltage magnitude at a bus.

The size of the jacobian was defined according to the number of generator buses in the total number of buses. Using two equations, namely,

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j)$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j)$$

Where, V_i, V_j are the node voltages, Y_{ij} is the nodal admittance of the i-j branch, θ_{ij} is the phase angle difference at the two ends of the admittance branch, and δ_i, δ_j are the phase angles of the voltage buses.

For every generator bus which is voltage controlled, only the active power equation is valid. For every load bus, both the active and reactive are valid. Thus if there are n number of total buses and m number of generator buses, then there shall be n-1 number of active power equations and n-m-1 number of reactive power equations. Since the slack bus is not included also the size of the Jacobian is therefore, (2n-m-2) x (2n-m-2).

In the new algorithm, the slack bus has been included in the matrix and also a new term P_B is being considered in the active power equation. Thus of course the NR matrix is modified. The P_1 and Q_1 terms are introduced into the Jacobian. Similarly on the other side of the equation, $\Delta\delta_1$ and $|V_1|$ are also introduced. But adding them directly won't go smoothly because now that the system is losing its reference. Moreover the participation factor is not reflecting itself upon the NR matrix. Hence a new term is added to the $\Delta\delta$ $|V|$ column matrix as ΔP_B which is the change in the power distribution at every generator bus with respect to the K_i value. Hence the new NR matrix looks like,

$$\begin{bmatrix} \Delta P_1 \\ \vdots \\ \Delta P_n \\ \Delta Q_1 \\ \vdots \\ \Delta Q_{n-m} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial \delta_1} & \cdots & \frac{\partial P_1}{\partial \delta_n} & \frac{\partial P_1}{\partial |V|_1} & \cdots & \frac{\partial P_1}{\partial |V|_{n-m}} & K_i \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{\partial P_n}{\partial \delta_1} & \cdots & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial |V|_1} & \cdots & \frac{\partial P_n}{\partial |V|_{n-m}} & K_n \\ \frac{\partial Q_1}{\partial \delta_1} & \cdots & \frac{\partial Q_1}{\partial \delta_n} & \frac{\partial Q_1}{\partial |V|_1} & \cdots & \frac{\partial Q_1}{\partial |V|_{n-m}} & \frac{\partial Q_1}{\partial P_B} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{\partial Q_{n-m}}{\partial \delta_1} & \cdots & \frac{\partial Q_{n-m}}{\partial \delta_n} & \frac{\partial Q_{n-m}}{\partial |V|_1} & \cdots & \frac{\partial Q_{n-m}}{\partial |V|_{n-m}} & \frac{\partial Q_{n-m}}{\partial P_B} \end{bmatrix} \begin{bmatrix} \Delta\theta_1 \\ \vdots \\ \Delta\theta_n \\ \Delta|V|_1 \\ \vdots \\ \Delta|V|_{n-m} \\ \Delta P_B \end{bmatrix}$$

If we take a closer look,

J1 J2 J5

$$\begin{bmatrix} \Delta P_1 \\ \vdots \\ \Delta P_n \\ \Delta Q_1 \\ \vdots \\ \Delta Q_{n-m} \end{bmatrix} = \left[\begin{array}{ccc|ccc|c} \frac{\partial P_1}{\partial \delta_1} & \cdots & \frac{\partial P_1}{\partial \delta_n} & \frac{\partial P_1}{\partial |V|_1} & \cdots & \frac{\partial P_1}{\partial |V|_{n-m}} & K_i \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{\partial P_n}{\partial \delta_1} & \cdots & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial |V|_1} & \cdots & \frac{\partial P_n}{\partial |V|_{n-m}} & K_n \\ \hline \frac{\partial Q_1}{\partial \delta_1} & \cdots & \frac{\partial Q_1}{\partial \delta_n} & \frac{\partial Q_1}{\partial |V|_1} & \cdots & \frac{\partial Q_1}{\partial |V|_{n-m}} & \frac{\partial Q_1}{\partial P_B} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{\partial Q_{n-m}}{\partial \delta_1} & \cdots & \frac{\partial Q_{n-m}}{\partial \delta_n} & \frac{\partial Q_{n-m}}{\partial |V|_1} & \cdots & \frac{\partial Q_{n-m}}{\partial |V|_{n-m}} & \frac{\partial Q_{n-m}}{\partial P_B} \end{array}\right] \begin{bmatrix} \Delta\theta_1 \\ \vdots \\ \Delta\theta_n \\ \Delta|V|_1 \\ \vdots \\ \Delta|V|_{n-m} \\ \Delta P_B \end{bmatrix}$$

J3 J4 J6

Here J1, J2, J3, J4 are the usual Jacobian sub matrices with the exception of including the slack bus or bus no.1 also in the calculations. The extra column added in the Jacobian is due to change in active and reactive power due to participation factor.

For J5, we have,

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) + K_i P_B \text{, for generator buses}$$

$$\frac{\partial P_i}{\partial P_B} = \mathrm{K_i} \text{ , for generator buses.}$$

$$\frac{\partial P_i}{\partial P_B} = 0 \text{, for load buses}$$

For J6 we have,

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j)$$

$$\therefore \frac{\partial Q_i}{\partial P_B} = 0$$

The final matrix becomes,

$$\begin{bmatrix} \Delta P_1 \\ \vdots \\ \Delta P_n \\ \Delta Q_1 \\ \vdots \\ \Delta Q_{n-m} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial \delta_1} & \cdots & \frac{\partial P_1}{\partial \delta_n} & \frac{\partial P_1}{\partial |V|_1} & \cdots & \frac{\partial P_1}{\partial |V|_{n-m}} & K_i \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & K_m \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_n}{\partial \delta_1} & \cdots & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial |V|_1} & \cdots & \frac{\partial P_n}{\partial |V|_{n-m}} & 0 \\ \frac{\partial Q_1}{\partial \delta_1} & \cdots & \frac{\partial Q_1}{\partial \delta_n} & \frac{\partial Q_1}{\partial |V|_1} & \cdots & \frac{\partial Q_1}{\partial |V|_{n-m}} & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{\partial Q_{n-m}}{\partial \delta_1} & \cdots & \frac{\partial Q_{n-m}}{\partial \delta_n} & \frac{\partial Q_{n-m}}{\partial |V|_1} & \cdots & \frac{\partial Q_{n-m}}{\partial |V|_{n-m}} & 0 \end{bmatrix} \begin{bmatrix} \Delta\theta_1 \\ \vdots \\ \Delta\theta_n \\ \Delta|V|_1 \\ \vdots \\ \Delta|V|_{n-m} \\ \Delta P_B \end{bmatrix}$$

3.3 ALGORITHM FOR THE NEW N-R MATRIX.

1. Assemble the line data, bus data, cost coefficients, MW limits in separate matrices.
2. Run a basic Newton-Raphson load flow analysis to gather preliminary values of Voltage magnitude, Phase angle, and Active and Reactive power at each bus.
3. Identify number of generator buses and number of load buses. Now include the slack bus as a generator bus as well.
4. Set the accuracy tolerance at a value ε.
5. Calculate K_i from the line flow data as, and assign it as K_{io}

$$K_{io} = \frac{P_{Gi}}{\sum_{i=1}^{m} P_{Gi}}$$

6. Initial values of P_B=0, $|V_i|^0$=1.0, δ_i^0=0.0, P_{sch} and Q_{sch} are provided.
7. The active and reactive power are calculated as,

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) + K_{i0}P_{B0}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j)$$

8. Change the NR matrix to accommodate slack bus and P_B
9. Set i=1 to 2n-m

   Set j=1 to 2n-m+1

10. If (i<=n && j<=n),

   Then, if i==j, find $\frac{\partial P_i}{\partial \delta_i} = \sum_{i \neq j} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j)$

   Else, find $\frac{\partial P_i}{\partial \delta_j} = -|V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j)$

11. If (i<=n && (j>n && j<=2n-m)),

Then, if j-n==I, find $\frac{\partial P_i}{\partial |V_i|} = 2|V_i||V_j|\cos\theta_{ii} + \sum_{i\neq j}|V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j)$

Else, find $\frac{\partial P_i}{\partial |V_j|} = |V_i||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j)$

12. If (i>n && j<=n),

Then, if i-n==j, find $\frac{\partial Q_i}{\partial \delta_i} = \sum_{i\neq j}|V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j)$

Else, find $\frac{\partial Q_i}{\partial \delta_j} = -|V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j)$

13. If (i>n && (j>n && j<=2n-m)),

Then, if i==j, find $\frac{\partial Q_i}{\partial |V_i|} = -2|V_i||V_j|\sin\theta_{ii} + \sum_{i\neq j}|V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j)$

Else, find $\frac{\partial Q_i}{\partial |V_j|} = -|V_i||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j)$

14. If j>2n-m,

Then, if i<=m, find, K_i

Else assign the place as 0.

15. Calculate $\Delta P_i=P_{sch}+P_i$ and $\Delta Q_i=Q_{sch}+Q_i$.

16. Solve the matrix using Gaussian Elimination or other iterative procedure

17. Find, $\delta_i=\delta_i^0+\Delta\delta_i$, $|V_i|=|V_i^0|+\Delta|V_i|$ and $P_B=P_{BO}+\Delta P_B$.

18. The process is continued till, $|\Delta P_i|<= \varepsilon$ and $|\Delta Q_i|<=\varepsilon$.

Chapter 4

RESULTS

1. Case Study I

5 Bus, 3 Generator Model

2. Case Study II

26 Bus, 6 Generator Model

Analysis of Results

4. RESULTS.

The above mentioned algorithm was implemented using a MATLAB code. The input was given using a 5 bus and a 26 bus system. Three different analyses was conducted on the two input bus systems, namely,

1. Ordinary Newton Raphson Load flow.
2. Ordinary Newton Raphson Load flow followed by ELD analysis using Coordination equations.
3. Newton Raphson Load flow followed by Distributed Slack algorithm ELD analysis.

The output data from the three cases were tabulated and compared to gather more information about the merits and demerits of Distributed Slack algorithm as discussed in this project. Standard load flow functions as given in [1] are used to implement the codes in MATLAB. Using the algorithm derived above, the functions are tweaked to accommodate the additional slack bus and participation factor parameters.

4.1 CASE STUDIES

1. A 5 Bus, 3 Generator Model.

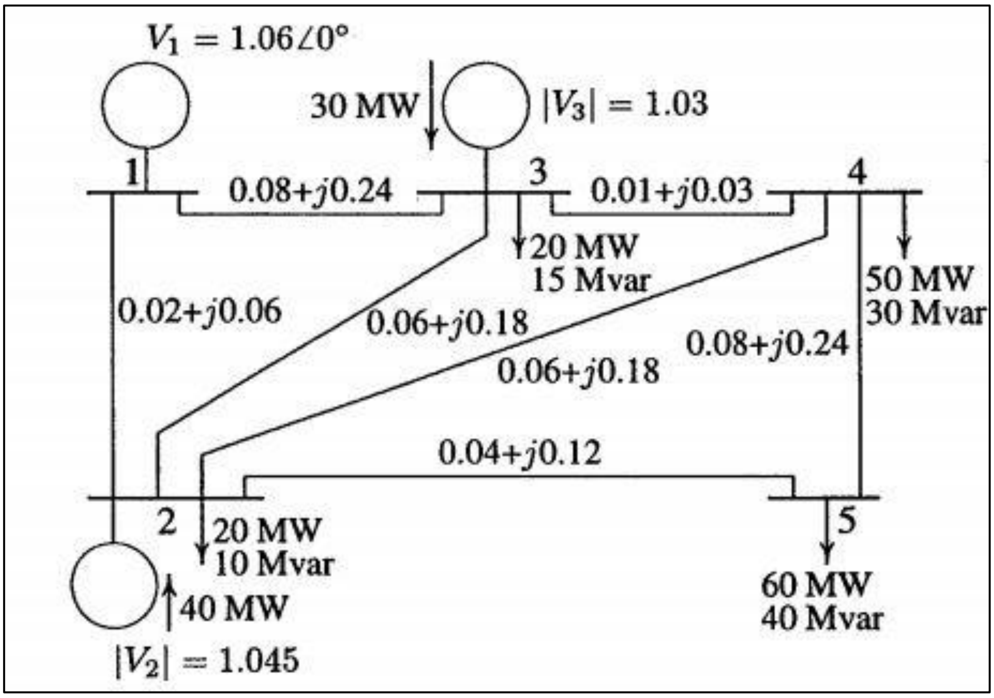

Figure 4.1. A 5 Bus 3 Generator Model

Input

```
%         Bus Bus  Voltage Angle -----Load----Generator--Static Mvar
%         No  code Mag.    Degree    MW    Mvar    MW Mvar Qmin Qmax
busdata=[1    1    1.06     0.0       0      0      0    0    10   50    0
          2    2    1.045    0.0      20     10     40   30    10   50    0
          3    2    1.03     0.0      20     15     30   10    10   40    0
          4    0    1.00     0.0      50     30      0    0     0    0    0
          5    0    1.00     0.0      60     40      0    0     0    0   0];

%                          Line code
%          Bus bus   R       X      1/2 B   = 1 for lines
%          nl  nr  p.u.   p.u.    p.u.
linedata=[1    2   0.02   0.06   0.030     1
           1    3   0.08   0.24   0.025     1
           2    3   0.06   0.18   0.020     1
           2    4   0.06   0.18   0.020     1
           2    5   0.04   0.12   0.015     1
           3    4   0.01   0.03   0.010     1
           4    5   0.08   0.24   0.025     1];

cost = [200  7.0    0.008
        180  6.3    0.009
        140  6.8    0.007];

mwlimits =[10  85
           10  80
           10  70];
```

Output

1. Ordinary Newton Raphson load flow only.

```
                    Power Flow Solution by Newton-Raphson Method
                       Maximum Power Mismatch = 1.43025e-005
                              No. of Iterations = 3

    Bus  Voltage  Angle    ------Load------    ---Generation---   Injected
    No.  Mag.     Degree     MW       Mvar       MW       Mvar       Mvar

     1   1.060    0.000     0.000     0.000    83.051     7.271     0.000
     2   1.045   -1.782    20.000    10.000    40.000    41.811     0.000
     3   1.030   -2.664    20.000    15.000    30.000    24.148     0.000
     4   1.019   -3.243    50.000    30.000     0.000     0.000     0.000
     5   0.990   -4.405    60.000    40.000     0.000     0.000     0.000

    Total                 150.000    95.000   153.051    73.230     0.000


B =

    0.0218    0.0093    0.0028
    0.0093    0.0228    0.0017
    0.0028    0.0017    0.0179


B0 =

    0.0003    0.0031    0.0015


B00 =

  3.0523e-004

Total system loss = 3.05248 MW

Total generation cost =    1633.24 $/h
>>
```

Figure 4.2. MATLAB Command Window output for ordinary NR load flow

2. Ordinary Newton Raphson load flow followed by ELD using coordination equations.

```
B =

    0.0472    0.0130    0.0036
    0.0130    0.0130    0.0010
    0.0036    0.0010    0.0115


B0 =

    0.0047    0.0012    0.0004


B00 =

  3.0516e-004

Total system loss = 2.15691 MW
Incremental cost of delivered power (system lambda) =  7.759051 $/MWh
Optimal Dispatch of Generation:

   23.5581
   69.5593
   59.0368

Absolute value of the slack bus real power mismatch, dpslack =   0.0009 pu
                   Power Flow Solution by Newton-Raphson Method
                      Maximum Power Mismatch = 1.90285e-008
                             No. of Iterations = 2

    Bus  Voltage  Angle    ------Load------    ---Generation---   Injected
    No.  Mag.     Degree     MW       Mvar       MW       Mvar       Mvar

     1   1.060    0.000     0.000     0.000    23.649    25.727     0.000
     2   1.045   -0.282    20.000    10.000    69.518    30.767     0.000
     3   1.030   -0.495    20.000    15.000    58.990    14.052     0.000
     4   1.019   -1.208    50.000    30.000     0.000     0.000     0.000
     5   0.990   -2.729    60.000    40.000     0.000     0.000     0.000

    Total                 150.000    95.000   152.157    70.545     0.000


Total generation cost =    1596.96 $/h
>>
```

Figure 4.3. MATLAB Command Window output for ordinary NR and ELD analysis

3. Newton Raphson Load flow followed by Distributed Slack algorithm ELD analysis.

```
B =

    0.0472    0.0130    0.0036
    0.0130    0.0130    0.0010
    0.0036    0.0010    0.0115


B0 =

    0.0047    0.0012    0.0004


B00 =

  3.0516e-004

Total system loss = 2.15689 MW
Incremental cost of delivered power (system lambda) =  7.759063 $/MWh
Optimal Dispatch of Generation:

   23.5566
   69.5600
   59.0377

Absolute value of the slack bus real power mismatch, dpslack =   0.0009 pu
                   Power Flow Solution by Newton-Raphson Method
                      Maximum Power Mismatch = 1.83635e-008
                             No. of Iterations = 2

    Bus  Voltage  Angle    ------Load------    ---Generation---   Injected
    No.  Mag.     Degree     MW       Mvar       MW       Mvar       Mvar

     1   1.060    0.000     0.000     0.000    23.646    25.728     0.000
     2   1.045   -0.282    20.000    10.000    69.520    30.766     0.000
     3   1.030   -0.495    20.000    15.000    58.992    14.052     0.000
     4   1.019   -1.207    50.000    30.000     0.000     0.000     0.000
     5   0.990   -2.729    60.000    40.000     0.000     0.000     0.000

    Total                 150.000    95.000   152.157    70.545     0.000


fx total generation cost = 1593.12 $/h
```

Figure 4.4. MATLAB Command Window output for Distributed Slack bus Load flow

Analysis of the output

N-R load flow Only		N-R load flow followed by ELD including losses.		N-R load flow followed by ELD using Distributed Slack.	
Plant 1 output	83.051 MW	Plant 1 output	23.649 MW	Plant 1 output	23.646 MW
Plant 2 output	40.000 MW	Plant 2 output	69.518 MW	Plant 2 output	69.520 MW
Plant 3 output	30.000 MW	Plant 3 output	58.990 MW	Plant 3 output	58.992 MW
Total system loss	3.0524 MW	Total system loss	2.1569 MW	Total system loss	2.1568 MW
Total generating cost	1633.24 $/h	Total generating cost	1596.96 $/h	Total generating cost	1593.12 $/h

Table 4.1. Result comparison among the three load flow algorithms used on the system

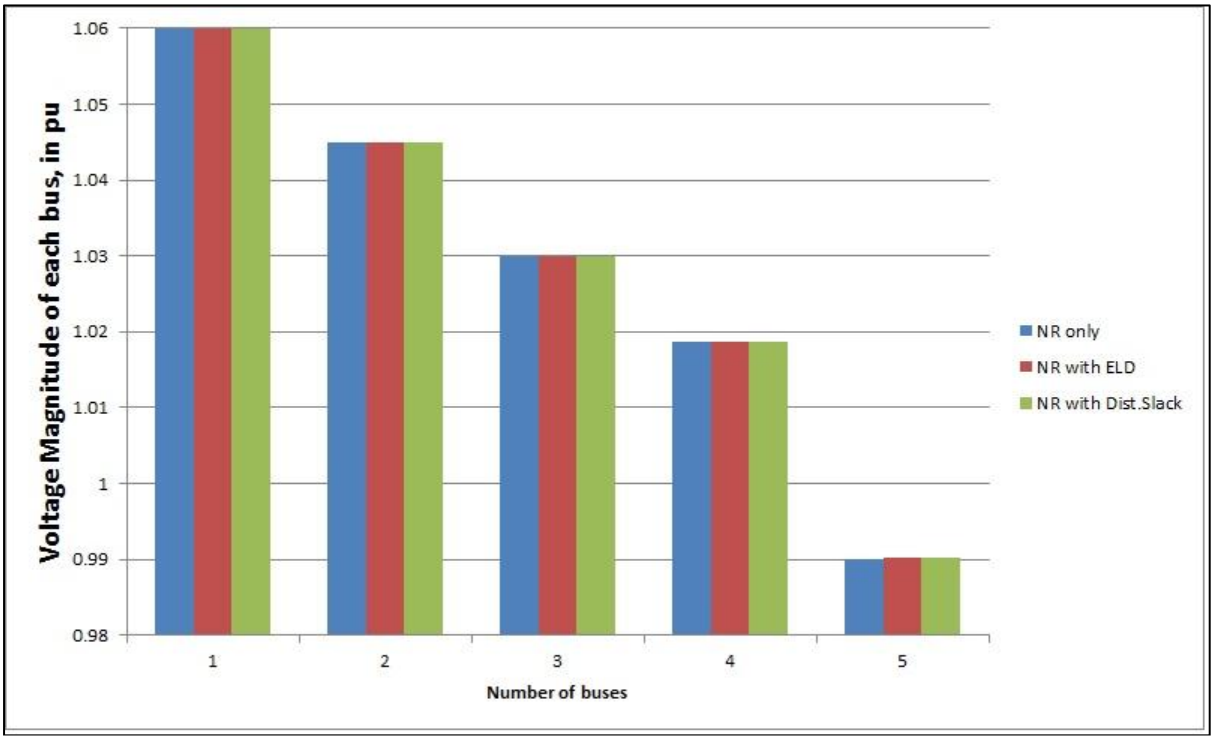

Figure 4.5. Comparison of Voltage magnitude of individual buses over the three algorithms

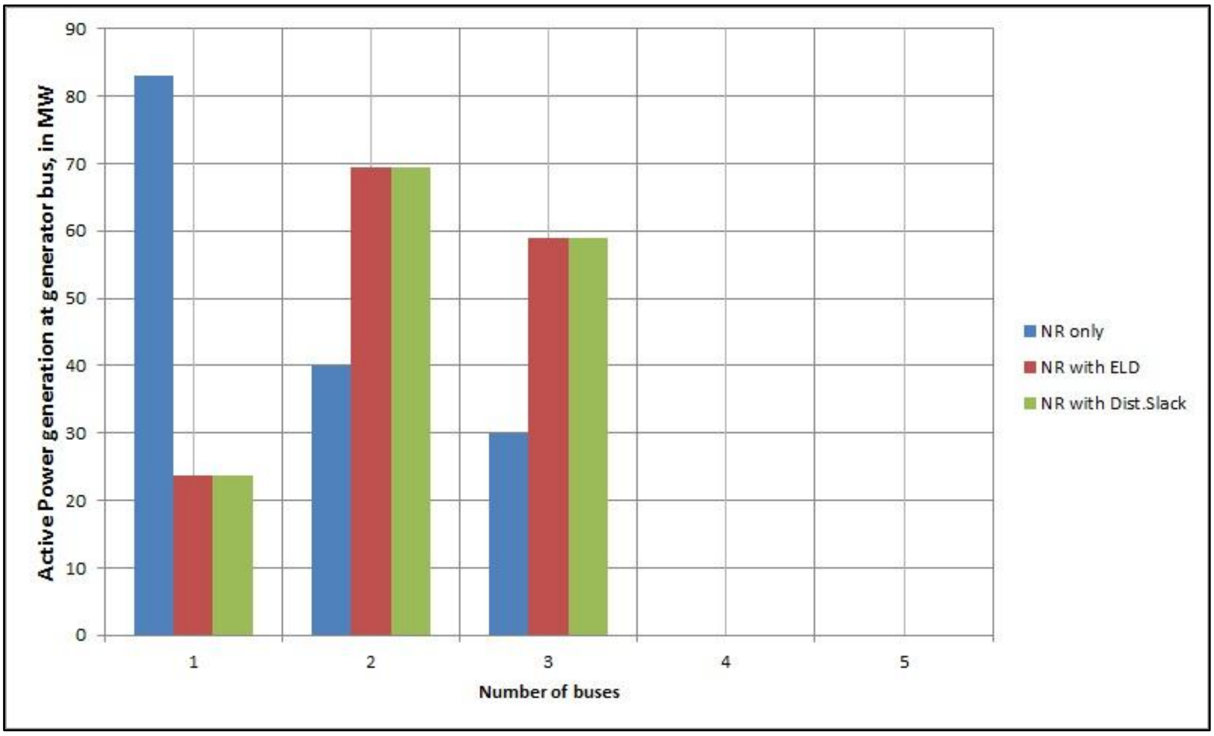

Figure 4.6. Comparison of Active Power generation of individual buses over the three algorithms

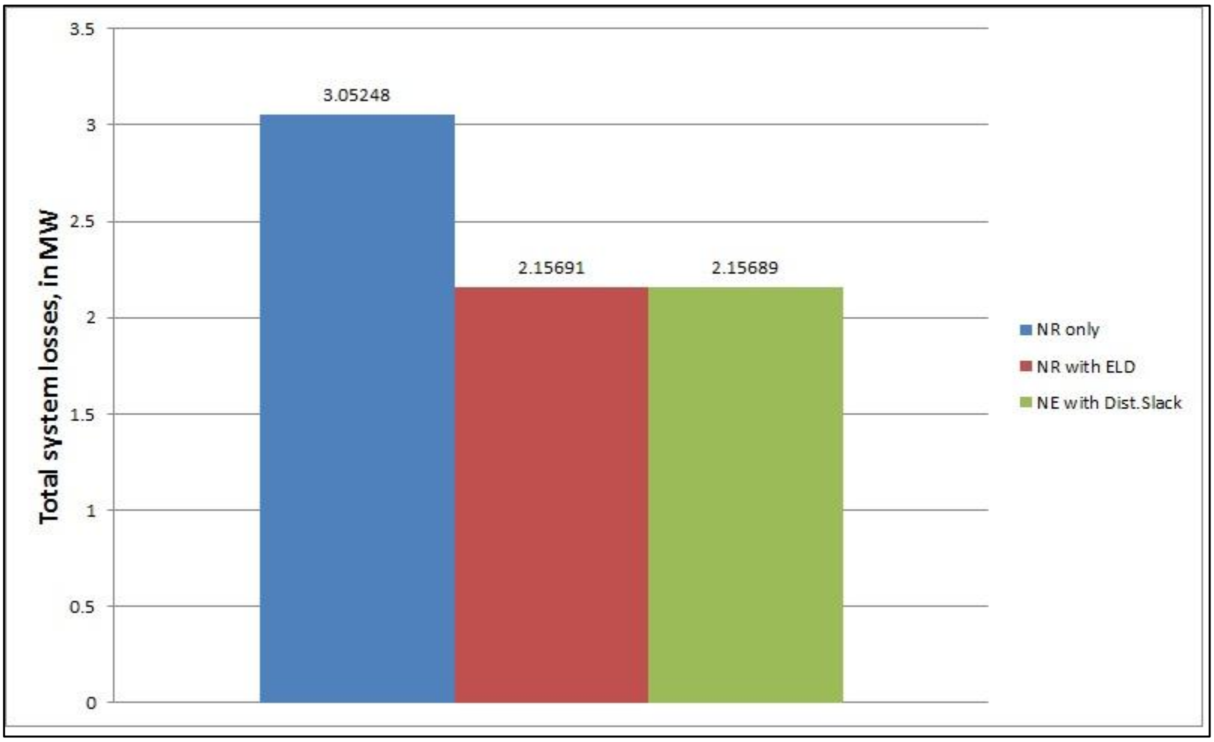

Figure 4.7. Comparison of Total System Loss of individual buses over the three algorithms

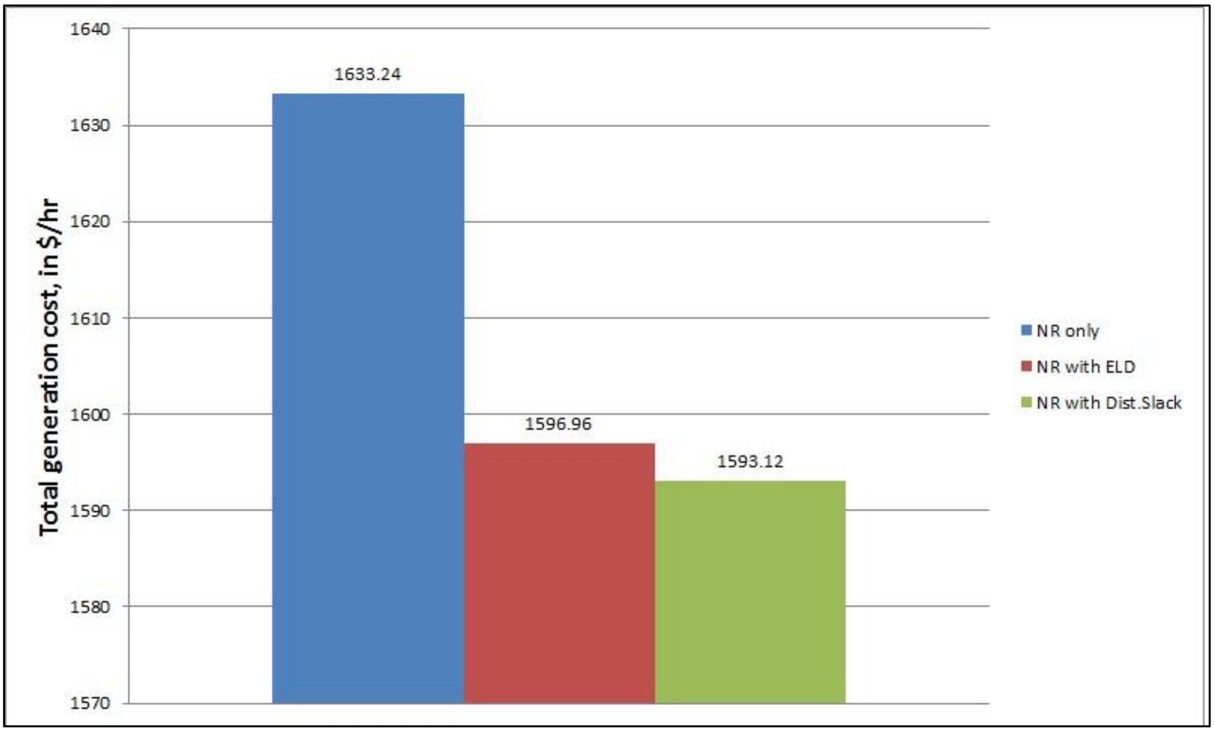

Figure 4.8. Comparison of Total Generation Cost of individual buses over the three algorithms

From the comparison above, we can conclude that,

1. The system voltage and active power generation at individual buses remains more or less constant in both conventional NR and distributed slack NR methods. This is good from a power engineer point of view as the parameters like insulation level and demand at each node will not be affected.
2. Total loss of the system stays almost the same in both conventional NR and distributed slack NR methods. This is understandable because the algorithm redistributes the said loss, and does not reduce it. The same amount of loss is now being distributed more economically.
3. The total generation cost in $/h is reducing by about 3.5$/h in distributed slack NR method as compared to conventional NR method. This happens due to the introduction of the participation factor in the load flow iterations leading to economical distribution of loss.

2. A 26 bus, 6 Generator Model.

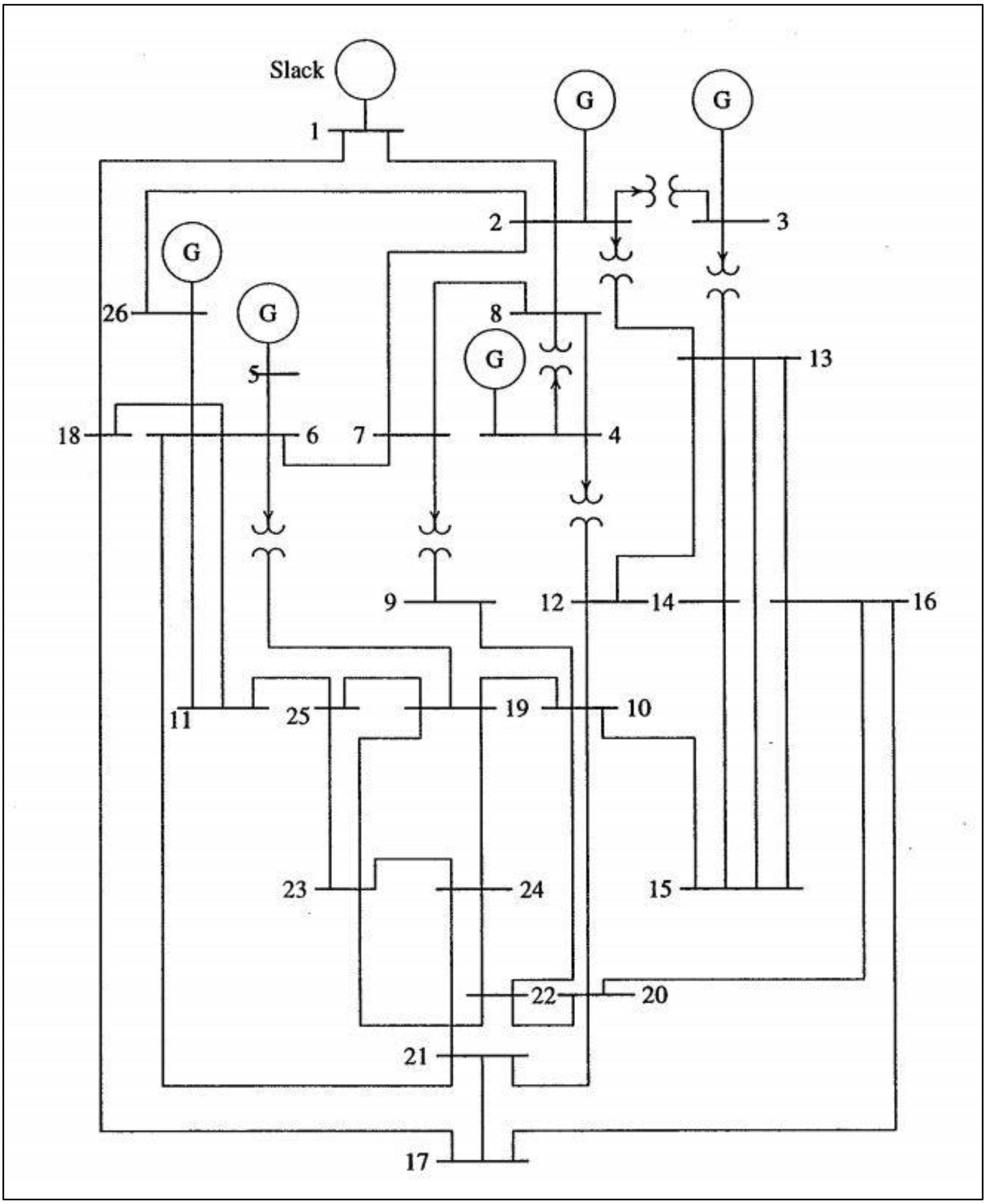

Figure 4.9. A 26 Bus 6 Generator Model

Input

```
%         Bus Bus  Voltage Angle   --Load-----Generator---Static Mvar
%         No  code Mag.    Degree  MW     Mvar  MW   Mvar Qmin Qmax
busdata=[1    1    1.025   0.0     51     41     0    0     0    0    4
         2    2    1.020   0.0     22     15    79    0    40  250    0
         3    2    1.025   0.0     64     50    20    0    40  150    0
         4    2    1.050   0.0     25     10   100    0    25   80    2
         5    2    1.045   0.0     50     30   300    0    40  160    5
         6    0    1.00    0.0     76     29     0    0     0    0    2
         7    0    1.00    0.0      0      0     0    0     0    0    0
         8    0    1.00    0.0      0      0     0    0     0    0    0
         9    0    1.00    0.0     89     50     0    0     0    0    3
        10    0    1.00    0.0      0      0     0    0     0    0    0
        11    0    1.00    0.0     25     15     0    0     0    0  1.5
        12    0    1.00    0.0     89     48    00   00     0    0    2
        13    0    1.00    0.0     31     15     0    0     0    0    0
        14    0    1.00    0.0     24     12     0    0     0    0    0
        15    0    1.00    0.0     70     31     0    0     0    0  0.5
        16    0    1.00    0.0     55     27     0    0     0    0    0
        17    0    1.00    0.0     78     38     0    0     0    0    0
        18    0    1.00    0.0    153     67     0    0     0    0    0
        19    0    1.00    0.0     75     15     0    0     0    0    5
        20    0    1.00    0.0     48     27     0    0     0    0    0
        21    0    1.00    0.0     46     23     0    0     0    0    0
        22    0    1.00    0.0     45     22     0    0     0    0    0
        23    0    1.00    0.0     25     12     0    0     0    0    0
        24    0    1.00    0.0     54     27     0    0     0    0    0
        25    0    1.00    0.0     28     13     0    0     0    0    0
        26    2    1.015   0.0     40     20    60    0    15   50   0];

%                       Line code
%          Bus bus   R        X        1/2 B    = 1 for lines
%          nl  nr  p.u.     p.u.     p.u.
linedata=[1    2   0.00055  0.00480  0.03000   1
          1   18   0.00130  0.01150  0.06000   1
          2    3   0.00146  0.05130  0.05000   0.96
```

2	7	0.01030	0.05860	0.01800	1
2	8	0.00740	0.03210	0.03900	1
2	13	0.00357	0.09670	0.02500	0.96
2	26	0.03230	0.19670	0.00000	1
3	13	0.00070	0.00548	0.00050	1.017
4	8	0.00080	0.02400	0.00010	1.050
4	12	0.00160	0.02070	0.01500	1.050
5	6	0.00690	0.03000	0.09900	1
6	7	0.00535	0.03060	0.00105	1
6	11	0.00970	0.05700	0.00010	1
6	18	0.00374	0.02220	0.00120	1
6	19	0.00350	0.06600	0.04500	0.95
6	21	0.00500	0.09000	0.02260	1
7	8	0.00120	0.00693	0.00010	1
7	9	0.00095	0.04290	0.02500	0.95
8	12	0.00200	0.01800	0.02000	1
9	10	0.00104	0.04930	0.00100	1
10	12	0.00247	0.01320	0.01000	1
10	19	0.05470	0.23600	0.00000	1
10	20	0.00660	0.01600	0.00100	1
10	22	0.00690	0.02980	0.00500	1
11	25	0.09600	0.27000	0.01000	1
11	26	0.01650	0.09700	0.00400	1
12	14	0.03270	0.08020	0.00000	1
12	15	0.01800	0.05980	0.00000	1
13	14	0.00460	0.02710	0.00100	1
13	15	0.01160	0.06100	0.00000	1
13	16	0.01793	0.08880	0.00100	1
14	15	0.00690	0.03820	0.00000	1
15	16	0.02090	0.05120	0.00000	1
16	17	0.09900	0.06000	0.00000	1
16	20	0.02390	0.05850	0.00000	1
17	18	0.00320	0.06000	0.03800	1
17	21	0.22900	0.44500	0.00000	1
19	23	0.03000	0.13100	0.00000	1
19	24	0.03000	0.12500	0.00200	1
19	25	0.11900	0.22490	0.00400	1

```
        20  21   0.06570  0.15700  0.00000   1
        20  22   0.01500  0.03660  0.00000   1
        21  24   0.04760  0.15100  0.00000   1
        22  23   0.02900  0.09900  0.00000   1
        22  24   0.03100  0.08800  0.00000   1
        23  25   0.09870  0.11680  0.00000   1];

cost = [240  7.0   0.007
        200  10    0.0095
        220  8.5   0.009
        200  11    0.009
        220  10.5  0.0080
        190  12    0.0075];

mwlimits =[100  500
           50   200
           80   300
           50   150
           50   200
           50   120];
```

Output

1. Ordinary Newton Raphson load flow only.

```
                 Power Flow Solution by Newton-Raphson Method
                    Maximum Power Mismatch = 3.18289e-010
                            No. of Iterations = 6

 Bus  Voltage  Angle    ------Load------    ---Generation---   Injected
 No.  Mag.     Degree     MW       Mvar       MW       Mvar      Mvar

  1   1.025    0.000    51.000    41.000   719.534   224.011    4.000
  2   1.020   -0.931    22.000    15.000    79.000   125.354    0.000
  3   1.035   -4.213    64.000    50.000    20.000    63.030    0.000
  4   1.050   -3.582    25.000    10.000   100.000    49.223    2.000
  5   1.045    1.129    50.000    30.000   300.000   124.466    5.000
  6   0.999   -2.573    76.000    29.000     0.000     0.000    2.000
  7   0.994   -3.204     0.000     0.000     0.000     0.000    0.000
  8   0.997   -3.299     0.000     0.000     0.000     0.000    0.000
  9   1.009   -5.393    89.000    50.000     0.000     0.000    3.000
 10   0.989   -5.561     0.000     0.000     0.000     0.000    0.000
 11   0.997   -3.218    25.000    15.000     0.000     0.000    1.500
 12   0.993   -4.692    89.000    48.000     0.000     0.000    2.000
 13   1.014   -4.430    31.000    15.000     0.000     0.000    0.000
 14   1.000   -5.040    24.000    12.000     0.000     0.000    0.000
 15   0.991   -5.538    70.000    31.000     0.000     0.000    0.500
 16   0.983   -5.882    55.000    27.000     0.000     0.000    0.000
 17   0.987   -4.985    78.000    38.000     0.000     0.000    0.000
 18   1.007   -1.866   153.000    67.000     0.000     0.000    0.000
 19   1.004   -6.397    75.000    15.000     0.000     0.000    5.000
 20   0.980   -6.025    48.000    27.000     0.000     0.000    0.000
 21   0.977   -5.778    46.000    23.000     0.000     0.000    0.000
 22   0.978   -6.437    45.000    22.000     0.000     0.000    0.000
 23   0.976   -7.087    25.000    12.000     0.000     0.000    0.000
 24   0.968   -7.347    54.000    27.000     0.000     0.000    0.000
 25   0.974   -6.775    28.000    13.000     0.000     0.000    0.000
 26   1.015   -1.803    40.000    20.000    60.000    32.706    0.000

 Total                1263.000   637.000  1278.534   618.791   25.000


B =

    0.0014    0.0015    0.0009   -0.0001   -0.0004   -0.0002
    0.0015    0.0043    0.0050    0.0001   -0.0008   -0.0003
    0.0009    0.0050    0.0315   -0.0000   -0.0020   -0.0016
   -0.0001    0.0001   -0.0000    0.0029   -0.0006   -0.0009
   -0.0004   -0.0008   -0.0020   -0.0006    0.0085   -0.0001
   -0.0002   -0.0003   -0.0016   -0.0009   -0.0001    0.0176
```

```
B0 =

   -0.0002   -0.0008    0.0067    0.0001    0.0000   -0.0012


B00 =

    0.0056

Total system loss = 15.53 MW

Total generation cost =   16760.73 $/h
>>
```

Figure 4.10. MATLAB Command Window output for ordinary NR load flow

2. Ordinary Newton Raphson load flow followed by ELD using coordination equations.

```
B =

    0.0017    0.0012    0.0007   -0.0001   -0.0005   -0.0002
    0.0012    0.0014    0.0009    0.0001   -0.0006   -0.0001
    0.0007    0.0009    0.0031    0.0000   -0.0010   -0.0006
   -0.0001    0.0001    0.0000    0.0024   -0.0006   -0.0008
   -0.0005   -0.0006   -0.0010   -0.0006    0.0129   -0.0002
   -0.0002   -0.0001   -0.0006   -0.0008   -0.0002    0.0150


B0 =

  1.0e-003 *

   -0.3908   -0.1297    0.7047    0.0591    0.2161   -0.6635


B00 =

    0.0056

Total system loss = 12.807 MW
Incremental cost of delivered power (system lambda) = 13.538113 $/MWh
Optimal Dispatch of Generation:

  447.6919
  173.1938
  263.4859
  138.8142
  165.5884
   87.0260

Absolute value of the slack bus real power mismatch, dpslack =   0.0008 pu
```

```
Power Flow Solution by Newton-Raphson Method
Maximum Power Mismatch = 2.33783e-005
No. of Iterations = 2
```

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar	Injected Mvar
1	1.025	0.000	51.000	41.000	447.611	250.582	4.000
2	1.020	-0.200	22.000	15.000	173.087	57.303	0.000
3	1.045	-0.639	64.000	50.000	263.363	78.280	0.000
4	1.050	-2.101	25.000	10.000	138.716	33.449	2.000
5	1.045	-1.453	50.000	30.000	166.099	142.890	5.000
6	1.001	-2.874	76.000	29.000	0.000	0.000	2.000
7	0.995	-2.406	0.000	0.000	0.000	0.000	0.000
8	0.998	-2.278	0.000	0.000	0.000	0.000	0.000
9	1.010	-4.387	89.000	50.000	0.000	0.000	3.000
10	0.991	-4.311	0.000	0.000	0.000	0.000	0.000
11	0.998	-2.824	25.000	15.000	0.000	0.000	1.500
12	0.994	-3.282	89.000	48.000	0.000	0.000	2.000
13	1.022	-1.261	31.000	15.000	0.000	0.000	0.000
14	1.008	-2.445	24.000	12.000	0.000	0.000	0.000
15	0.999	-3.229	70.000	31.000	0.000	0.000	0.500
16	0.990	-3.990	55.000	27.000	0.000	0.000	0.000
17	0.983	-4.366	78.000	38.000	0.000	0.000	0.000
18	1.007	-1.884	153.000	67.000	0.000	0.000	0.000
19	1.005	-6.074	75.000	15.000	0.000	0.000	5.000
20	0.983	-4.759	48.000	27.000	0.000	0.000	0.000
21	0.977	-5.411	46.000	23.000	0.000	0.000	0.000
22	0.980	-5.325	45.000	22.000	0.000	0.000	0.000
23	0.978	-6.388	25.000	12.000	0.000	0.000	0.000
24	0.969	-6.672	54.000	27.000	0.000	0.000	0.000
25	0.975	-6.256	28.000	13.000	0.000	0.000	0.000
26	1.015	-0.284	40.000	20.000	86.939	27.892	0.000
Total			1263.000	637.000	1275.815	590.396	25.000

```
Total generation cost =    15447.72 $/h
>>
```

Figure 4.11. MATLAB Command Window output for ordinary NR and ELD analysis

3. Newton Raphson Load flow followed by Distributed Slack algorithm ELD analysis.

```
B =

    0.0017    0.0012    0.0007   -0.0001   -0.0005   -0.0002
    0.0012    0.0014    0.0009    0.0001   -0.0006   -0.0001
    0.0007    0.0009    0.0031    0.0000   -0.0010   -0.0006
   -0.0001    0.0001    0.0000    0.0024   -0.0006   -0.0008
   -0.0005   -0.0006   -0.0010   -0.0006    0.0129   -0.0002
   -0.0002   -0.0001   -0.0006   -0.0008   -0.0002    0.0150


B0 =

  1.0e-003 *

   -0.3908   -0.1297    0.7046    0.0591    0.2162   -0.6635


B00 =

    0.0056

Total system loss = 12.8072 MW
Incremental cost of delivered power (system lambda) = 13.538140 $/MWh
Optimal Dispatch of Generation:

  447.6940
  173.1954
  263.4876
  138.8157
  165.5807
   87.0277

Absolute value of the slack bus real power mismatch, dpslack =   0.0007 pu
                   Power Flow Solution by Newton-Raphson Method
                      Maximum Power Mismatch = 1.94536e-005
                             No. of Iterations = 2

    Bus  Voltage  Angle    ------Load------    ---Generation---   Injected
    No.  Mag.     Degree     MW       Mvar       MW       Mvar       Mvar

     1   1.025    0.000    51.000    41.000   447.621   250.582    4.000
     2   1.020   -0.200    22.000    15.000   173.098    57.300    0.000
     3   1.045   -0.639    64.000    50.000   263.377    78.278    0.000
     4   1.050   -2.101    25.000    10.000   138.726    33.449    2.000
     5   1.045   -1.454    50.000    30.000   166.049   142.899    5.000
     6   1.001   -2.875    76.000    29.000     0.000     0.000    2.000
     7   0.995   -2.407     0.000     0.000     0.000     0.000    0.000
     8   0.998   -2.278     0.000     0.000     0.000     0.000    0.000
```

9	1.010	-4.387	89.000	50.000	0.000	0.000	3.000
10	0.991	-4.311	0.000	0.000	0.000	0.000	0.000
11	0.998	-2.824	25.000	15.000	0.000	0.000	1.500
12	0.994	-3.282	89.000	48.000	0.000	0.000	2.000
13	1.022	-1.261	31.000	15.000	0.000	0.000	0.000
14	1.008	-2.445	24.000	12.000	0.000	0.000	0.000
15	0.999	-3.229	70.000	31.000	0.000	0.000	0.500
16	0.990	-3.990	55.000	27.000	0.000	0.000	0.000
17	0.983	-4.367	78.000	38.000	0.000	0.000	0.000
18	1.007	-1.884	153.000	67.000	0.000	0.000	0.000
19	1.005	-6.074	75.000	15.000	0.000	0.000	5.000
20	0.983	-4.759	48.000	27.000	0.000	0.000	0.000
21	0.977	-5.411	46.000	23.000	0.000	0.000	0.000
22	0.980	-5.326	45.000	22.000	0.000	0.000	0.000
23	0.978	-6.388	25.000	12.000	0.000	0.000	0.000
24	0.969	-6.672	54.000	27.000	0.000	0.000	0.000
25	0.975	-6.256	28.000	13.000	0.000	0.000	0.000
26	1.015	-0.284	40.000	20.000	86.946	27.891	0.000
Total			1263.000	637.000	1275.815	590.398	25.000

total generation cost = 15441.39 $/h

Figure 4.12. MATLAB Command Window output for Distributed Slack bus Load flow

Analysis of the output

N-R load flow Only		N-R load flow followed by ELD including losses.		N-R load flow followed by ELD using Distributed Slack.	
Plant 1 output	719.53 MW	Plant 1 output	447.611 MW	Plant 1 output	447.62 MW
Plant 2 output	79.00 MW	Plant 2 output	173.087 MW	Plant 2 output	173.09 MW
Plant 3 output	20.00 MW	Plant 3 output	263.362 MW	Plant 3 output	263.37 MW
Plant 4 output	100.00 MW	Plant 4 output	138.716 MW	Plant 4 output	138.72 MW
Plant 5 output	300.00 MW	Plant 5 output	166.099 MW	Plant 5 output	166.05 MW
Plant 6 output	60.00 MW	Plant 6 output	86.939 MW	Plant 6 output	86.946 MW
Total system loss	15.53 MW	Total system loss	12.807 MW	Total system loss	12.807 MW
Total generating cost	16760.73 $/h	Total generating cost	15447.7 $/h	Total generating cost	15441.4 $/h

Table 4.2. Result comparison among the three load flow algorithms used on the system

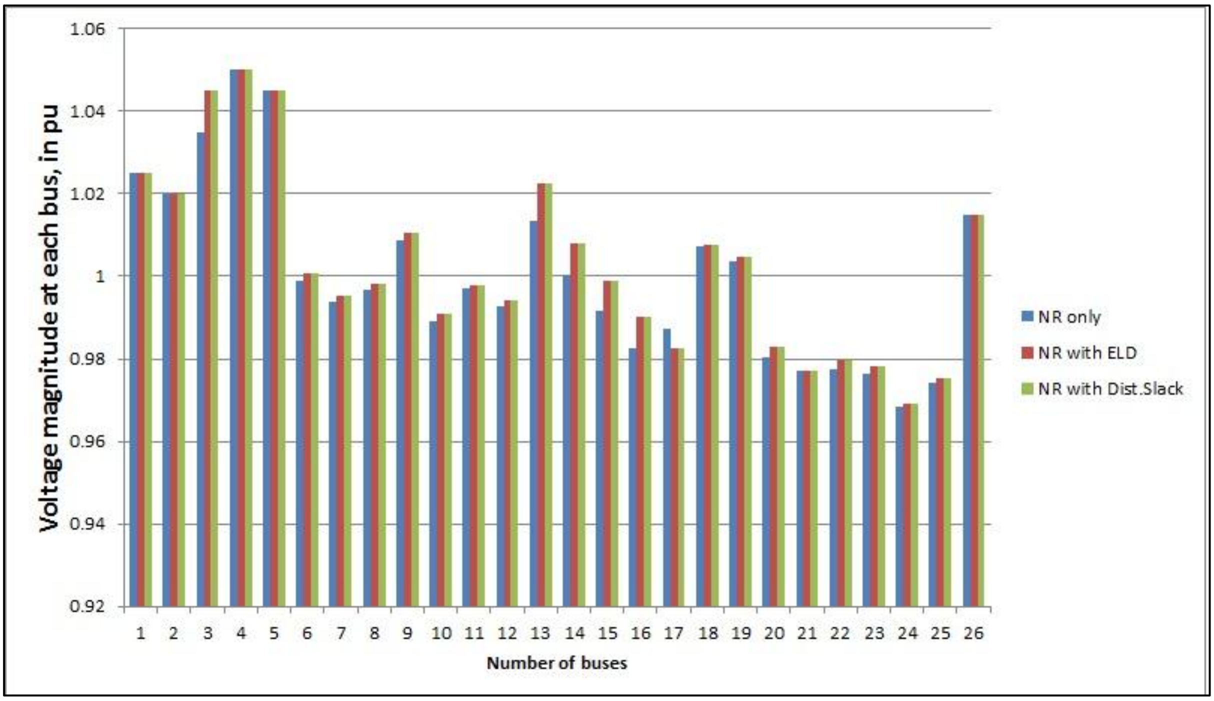

Figure 4.13. Comparison of Voltage magnitude of individual buses over the three algorithms

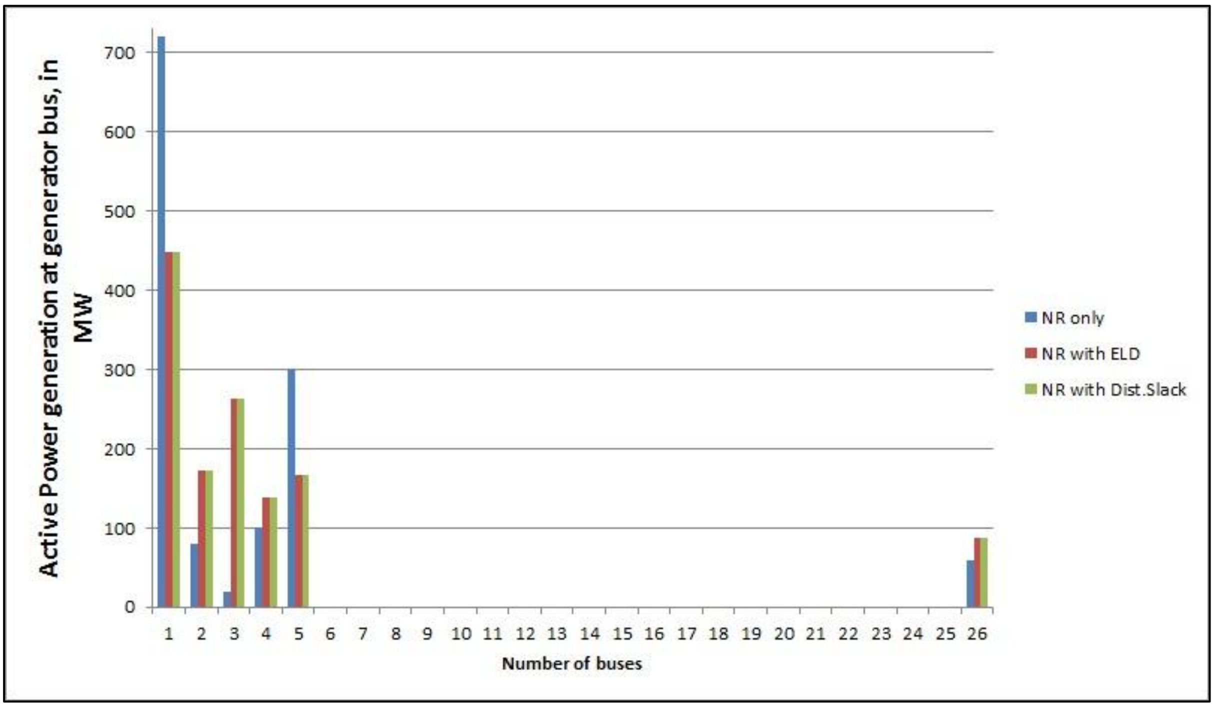

Figure 4.14. Comparison of Active Power generation of individual buses over the three algorithms

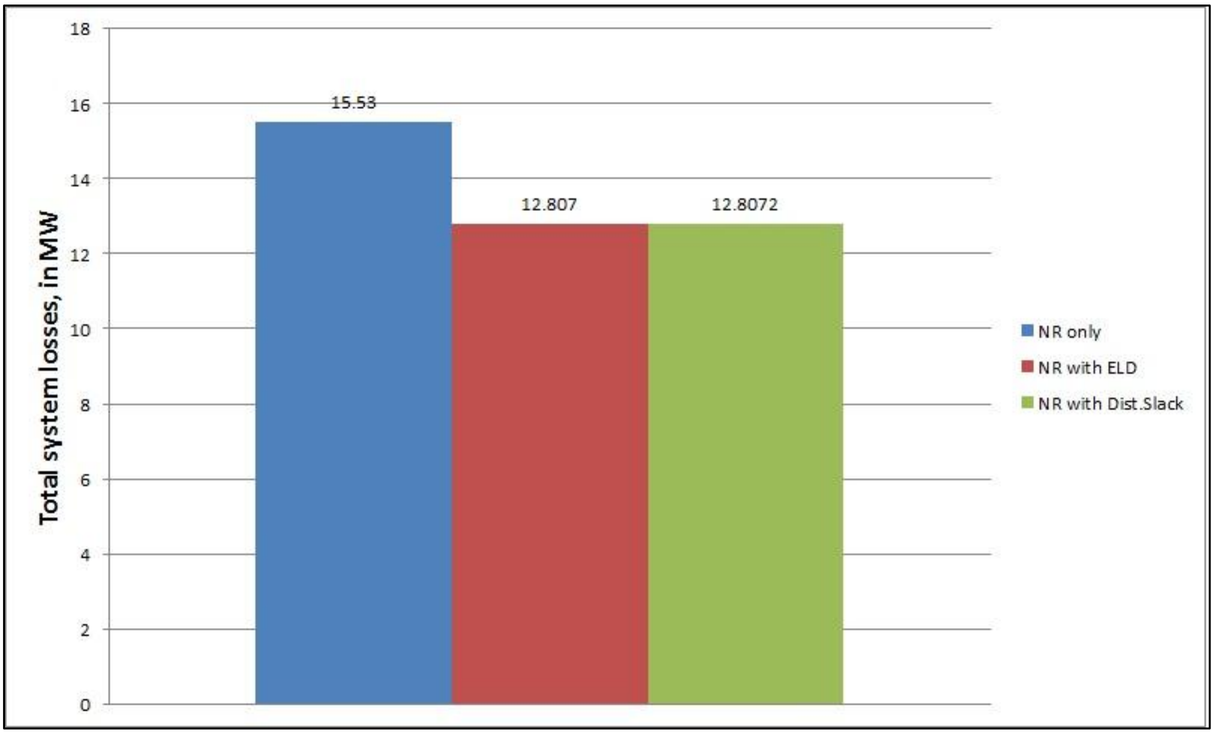

Figure 4.15. Comparison of Total System Loss of individual buses over the three algorithms

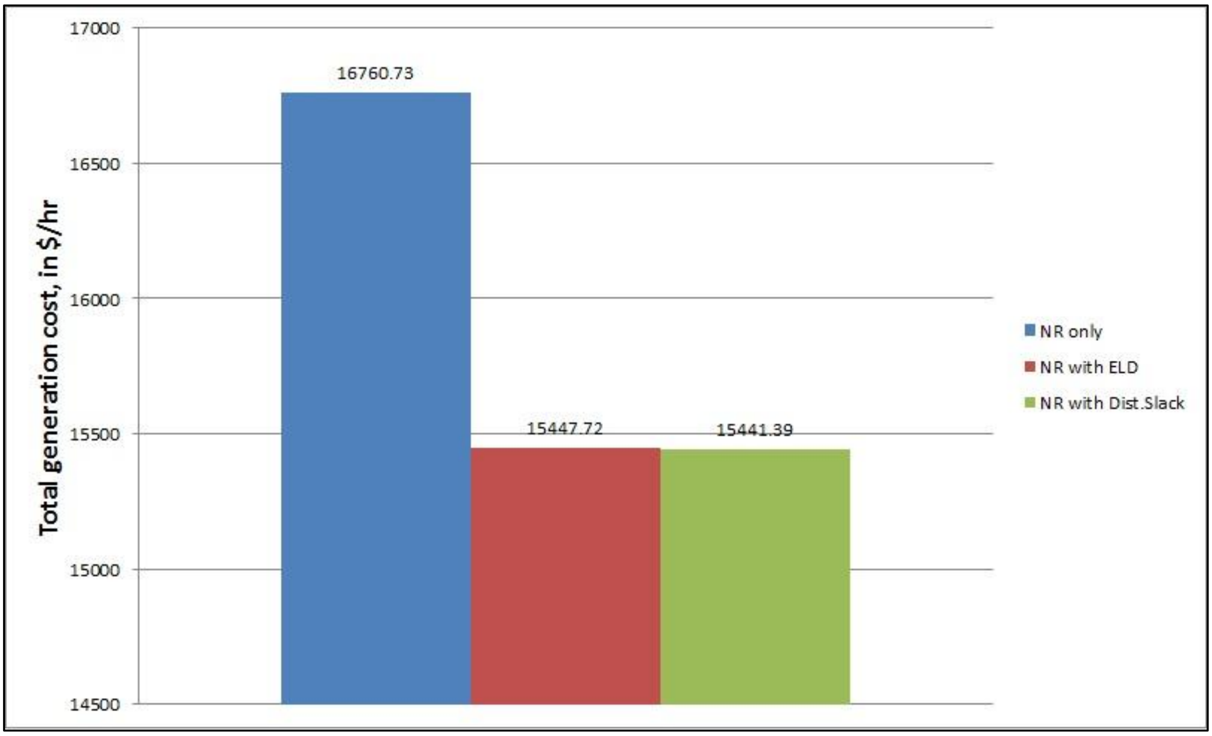

Figure 4.16. Comparison of Total Generation Cost of individual buses over the three algorithms

From the comparison above, we can conclude that,

1. The system voltage and active power generation at individual buses remains more or less constant in both conventional NR and distributed slack NR methods. This is good from a power engineer point of view as the parameters like insulation level and demand at each node will not be affected.
2. Total loss of the system stays almost the same in both conventional NR and distributed slack NR methods. This is understandable because the algorithm redistributes the said loss, and does not reduce it. The same amount of loss is now being distributed more economically. The system does not show any major deviation due to the increase in size of the system in concern from 5 bus to 26 bus model.
3. The total generation cost in $/h is reducing by about 6.2 $/h in distributed slack NR method as compared to conventional NR method. This happens due to the introduction of the participation factor in the load flow iterations leading to economical distribution of loss. It is seen that the reduction in generation cost has increased slightly from that of the 5 bus model. Thus we can make a conclusion that with the increase in number of generators in the system, the reduction in generation cost will increase as the redistribution of losses can take place more economically with more number of generators.

Chapter 5

CONCLUSION

5. CONCLUSION

1. The distributed slack bus algorithm for ELD analysis can serve as a vital tool for reducing generation costs.
2. However it does not have a major impact on the total system losses.
3. The savings in generation cost keeps increasing with the increase in number of generators attached to the system.
4. The participation factor defines the total savings garnered. Anybody modelling a power system can change the K_i suitable to that system and have a separate ELD algorithm.
5. The program can be implemented using standard open source MATLAB load flow functions by making minor changes to the NR matrix.
6. The distributed slack bus algorithm though can sometimes make the system ill-conditioned and lead to premature termination of iterations. This may be due to the choice of K_i or due to some other reasons. Hence before using the algorithm, it must be checked if the system shall behave erratic or not.

A MATLAB code was formed using standard load flow functions used in [5]. The three different algorithms were implemented on two case studies and the values were tabulated and compared.

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